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Aiming towards pollution free future by high penetration of renewable energy sources in electricity generation expansion planning

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ABSTRACT

Global climate change is the biggest challenge to decide on the energy and environmental policy. Reducing greenhouse gases (GHG) emission would confine hazardous effects of global warming. United Nations Climate Change Conference reported that global GHG emission rate has elevated by an average of 3% annually. In this context, the state of Tamil Nadu in India emits 51.42 Million Tons CO_2 equivalent as reported by Tamil Nadu Carbon Footprint study carried out by Confederation of Indian Industry (CII). The study aims to meliorate astute plan for electricity generation expansion that would create a paragon future with low carbon emission. Combined utilization of Long-Range Energy Alternative Planning (LEAP) and EnergyPLAN software is done in this paper. Electricity demand, installation capacity and power production with overall cost and total GHG emission are planned till the year 2030 using LEAP. Baseline and GHG mitigation are the modeled scenarios with 2016 as the base year. The GHG mitigation scenario emits lesser GHG than the baseline scenario. The results of LEAP suggest to adopt GHG mitigation scenario and therefore the expansion capacities of power plants planned by this GHG mitigation scenario is given as input to EnergyPLAN software for monthly and hourly basis planning.

1. Introduction

Global warming, also mentioned as climate change, is the rise in the average temperature of the Earth's climate system. Multiple evidences show that the global warming takes place continuously. It is caused by a wide range of human activities (Gillis, 2015). It is evident that surface temperature of the planet is increased by 1 °F in the 20th century and would further increase in the future. The Intergovernmental Panel on Climate Change (IPCC) is the scientific advisory committee formed by the United Nations to investigate the global climate change. They have reported that global temperatures might elevate from 1.6 °F to 6.3 °F by the year 2100 (Climate Change, 2016). These elevating environmental temperature leads to global warming and it is a serious threat to human health. These adverse changes specifically due to greenhouse gases (GHG) emission have brought us to the situation of lethal implications deteriorating healthy ambiance for survival (Jane, 2015; Malaria, 2016). Irregular rainfall patterns are the proof of cardinal effects due to the artificially raised GHG concentration. The various evidences that strengthens the relation between climate change and heavy rainfall are presented (Adve, 2016). Unstable sea water level is very frequent in Tamil Nadu coastal region and the impacts of climate

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change on the sea level on the east coast of Tamil Nadu have been presented (Achyuthan & Baker, 2002). The backbone of Tamil Nadu's growth rate highly depends on agriculture. Changing weather patterns associated with changing global climate patterns pose significant challenges for the farmers, small and large, who feeds the growing population of Tamil Nadu. So, it is urge to identify the sources of GHG emission and mitigate them.

Energy-related human activities are responsible for 86% of all GHG emissions in which 36% is contributed by the power plants and other electricity generation methods (Climate Change, 2016). These measures are an indication that makes unfavorable temperature rise as a prime cause for raising global temperature. The coal power plants supply 40% of the total energy generated (Generation, 2016). CO_2 emission from coal is higher than oil or natural gas. With concern to this minimizing the high dependence on coal plants would be a possible solution to reduce the GHG emission to a large extent. In a futurist perceptive, a clear discussion on the climate change, the scenarios involved in Global Trends 2030 (GT-2030) (Kapoor, 2013) and five prominent approaches on future climate change (Gidley, 2016) have been presented.

In this context, electricity Generation Expansion Planning (GEP) problem plays a very important role in a national or state power system for the selection of power generating units, deciding the timing of investments and optimal fuel mix pattern of generating units over short-term or long-term planning horizon (Khokhar, 1997; Wang & McDonald, 1994). GEP can be mathematically modeled as a large-scale combinatorial dynamic optimization problem with numerous constraints. The optimization of GEP involves satisfying the following four basic factors with the aim of confirming that the installed capacity sufficiently meets the forecasted demand over the planning horizon:

WHAT - types of generation units need to be installed

HOW MUCH - capacity of each candidate generation unit needs to be added

WHERE - the generation units to be sited

WHEN - the stage or year of the planning horizon when the candidate units need to be installed.

The authors previously applied eight meta-heuristic techniques to solve GEP problem, and concluded that Differential Evolution (DE) performed well compared to the other meta-heuristic techniques (Kannan, Slochanal, & Padhy, 2005). In order to avoid extensive computational time Self-adaptive Differential Evolution (SaDE) was proposed to solve GEP problem (Karthikeyan, Kannan, Baskar, & Thangaraj, 2013). In order to achieve better results, Opposition-based Differential Evolution (ODE) had been applied to solve the GEP problem (Karthikeyan, Kannan, Baskar, & Thangaraj, 2013). The GEP problem was solved for Tamil Nadu for long term horizon using a state-of-the-art computer package, Wien Automatic System Planning IV (WASP-IV) (Karunanithi, Kannan, & Thangaraj, 2015). Recently, the modeling studies carried out to demonstrate the impact of bringing in solar plants into the generating system as a technology alternative power plant are presented (Rajesh, Bhuvanesh, Kannan, & Thangaraj, 2016). The GEP modeling studies are carried out for a candidate power system, to investigate the impact of the introduction of solar power plant with storage facility (Rajesh, Bhuvanesh et al., 2016; Rajesh, Kannan, & Thangaraj, 2016). The least cost generation expansion planning with wind power plant incorporating emission using DE is presented (Bhuvanesh, Karunanithi, & Kannan, 2014; Rajesh, Bhuvanesh et al., 2016; 2016b). An investigation on the economic and environmental impact of penetrating RES into the peak deficit power system of Tamil Nadu using the Long-Range Energy Alternative Planning system (LEAP) by integrating Demand Side Management (DSM) and Supply Side Management (SSM) strategies has been made (Karunanithi, Saravanan, Prabakar, Kannan, & Thangaraj, 2017). The results show that simultaneous implementation of DSM and SSM strategies reduces Total Installed Capacity (TIC) by 10%, Net Present Value (NPV) of investments by 18%, one hundred year global warming potential (CO_2E) by 23%, Energy Not Served (ENS) by 18% and increases Flexibility Index (FI) by 20%.

In this work, GEP is carried out for the state Tamil Nadu to reduce the GHG emission while generating electricity.

The objectives of this research work are:

1 To model a GHG mitigation scenario using LEAP for expanding the power generation of the power system of Tamil Nadu until the year 2030, by having 2016 as the base year.
2 To forecast the electrical energy demand, the capacity to be installed, electric power to be produced by each type of power plant, the overall cost of electricity production and total GHG emission for generating electricity until the year 2030 through simulation using LEAP.
3 To extract the range of various technologies for expanding power generation with low GHG emission specifically for the year 2030 from the GHG mitigation scenario using LEAP and give the expansion capacities of power plants as input to the energy modeling software EnergyPLAN, for obtaining the monthly and hourly basis plan.

2. LEAP and ENERGYPLAN

The LEAP model is a fixed energy-economy-environment model developed by the Stockholm Environment Institute since the early 1980s (Wei, Wu, Fan, & Liu, 2006). This model plans the energy demand, energy consumption and environmental impact by investigating the economic benefits of each energy scenario in detail. The model is based on simulation of the energy system and it is called an end-use energy consumption model (Siteur, 2004). Numerous studies have been conducted using the LEAP model so far in different countries in the world. LEAP has the ability to calculate the optimal expansion of power plants for the electricity system, at least cost, over the whole period of calculation (from the base year to the end year). A least cost system can be planned subject to a number of user-specified constraints including maximum annual levels of emissions of pollutants such as CO_2, N_2O, CH_4, etc. and minimum or maximum capacities for individual plant types. An expansion pathway for an energy system that satisfy a minimum renewable portfolio standard with a target for reducing GHG emissions was also explained (Heaps, 2012). The primary objective of

energy planning is not to identify a single optimal solution, but rather to identify strong energy policies that work well under a range of reasonable input assumptions.

An energy modeling software namely EnergyPLAN, has been developed and expanded on a continuous basis since 1999 at Aalborg University, Denmark (Lund & Münster, 2003a). The purpose of the tool is to promote the design of national or regional energy plan strategies by simulating the entire energy system, which includes heat and electricity supplies as well as the transport and industrial sectors. It is a deterministic input-output tool and the general inputs to be given are demands, RES, energy station capacities, costs, and a number of different regulation strategies for import/export and excess electricity production. Outputs are energy balances with resulting annual productions, fuel consumption, import/export of electricity, and total costs including income from the exchange of electric power. In its programming, any procedures, which would increase the calculation time have been avoided, and the computation for 1 year requires only a few seconds on an average computer. Finally, EnergyPLAN optimizes the operation of a given system as opposed to tools, which optimize investments in the system (Connolly, Lund, Mathiesen, & Leahy, 2010).

Recently, the present status of power generation and various potential future scenarios and the associated impacts on the system marginal cost, global warming potential, and resource diversity index in Panama (McPherson & Karney, 2014) and Venezuelan (Bautista, 2012) power generation sectors are presented. The integration of flexible regulation systems like Combined Heat and Power (CHP) is suggested and investments are made in heat pumps (Lund, 2005). The systems have been analyzed for their ability to evade excess production and to use trade on the electricity market. The issues of introducing RES into Danish reference system with a high degree of CHP is presented (Lund & Münster, 2003b; Lund, 2005). The addition of electric vehicles (EVs) and 'vehicle-to-grid" (V2G) technology into the energy systems of Denmark permits huge wind energy penetration without excess electricity production, and minimizes CO_2 emissions significantly (Lund & Kempton, 2008).

An approach to evaluate the best operational strategy and the computer tool to implement that strategy for recognizing optimal CHP plant designs is presented (Lund & Andersen, 2005). The impacts of introducing flexible regulation systems, such as CHP units involved in the regulation and potential investments in heat pumps as well as heat storage facilities have been discussed for Denmark (Lund & Münster, 2006). The problems and perceptions which may arise in converting Denmark energy systems into a 100% RES system have been presented (Lund, 2007). A study has been performed for utilizing organic waste for heat and power production as well as fuel for transport using different technologies such as second-generation biofuel production, gasification, fermentation and improved incineration (Münster & Lund, 2009). Seven different integration technologies to penetrate CHP and RES have been analyzed to enhance the balance between demand and supply in a sustainable energy system of Denmark (Mathiesen & Lund, 2009; Mathiesen, 2008). The application of thermoelectric generators (TEG) for district heating systems and power plants to model an efficient energy plan for Denmark had been presented (Chen, Lund, Rosendahl, & Condra, 2010).

The influence of storage and relocation options, such as energy storage technologies (EST), pumped hydro storage, compressed air energy storage and biomass gasification, hydrogen production and storage, and V2G systems on West Danish energy system had been studied (Blarke & Lund, 2008). A detailed study had been made to investigate the impact of introducing RES with compressed air energy storage (CAES) into energy system (Lund & Salgi, 2009; Lund, Salgi, Elmegaard, & Andersen, 2009). A comparison had been made between two policies such as, export policy and self-supply policy to generate clean energy with low CO_2 emission for Denmark. The authors recommended to follow self-supply policy (Lund & Clark, 2002). Moreover, EnergyPLAN was used to analyze the potential of CHP and renewable energy in Estonia, Germany, Poland, Spain, and UK (DESIRE, 2016). EnergyPLAN has been used to simulate a 100% renewable energy system for the island of Mljet in Croatia (Lund, Duić, Krajac˘ić, & Graça Carvalho, 2007) as well as the countries of Ireland (Connolly, Lund, Mathiesen, & Leahy, 2009) and Denmark (Mathiesen, 2009). Recently, an integrated assessment for energy planning and climate change mitigation in Mexico (Elizondo, Pérez-Cirera, Strapasson, Fernández, & Cruz-Cano, 2017) has been investigated.

Out of preceding scientific reports and research outcomes published earlier, solutions for electricity GEP problem have been provided either by LEAP or EnergyPLAN. The usage of LEAP would result in modeling of GEP based only on yearly basis. Though yearly basis plan would solve GEP yet power system reliability is found indeterminate. With this state of affair, there is a need for hourly based electricity generation expansion plan that assures power system reliability. To our knowledge this study would be the first attempt that incorporates two different energy modeling tool (LEAP and EnergyPLAN) for electricity generation expansion plan. This potentiates an undeviating hourly based GEP that could encounter any power crisis with minimal GHG emission.

3. LEAP model for Tamil Nadu

Tamil Nadu Electricity Board (TNEB) is a power generation and distribution company owned by Government of Tamil Nadu. TNEB was restructured on 1.11.2010 into TNEB Limited, Tamil Nadu Generation and Distribution Corporation Limited (TANGEDCO) and Tamil Nadu Transmission Corporation Limited (TANTRANSCO). In Tamil Nadu almost 100% of households have electricity as the source of lighting as from 2015 (Indian states ranking by households having electricity, 2016).

The scheme "Tamil Nadu Vision: 2023" was commissioned by the state government to eliminate the present energy insufficiency. With urge to the situation the commission have enforced expeditious addition for conventional, non-conventional power generation capacity and renovation of transmission and distribution infrastructure with an investment of Rs.4,50,000 crore for the next eleven years (The Vision Tamil Nadu 2023; Strategic Plan for Infrastructure Development in Tamil Nadu, 2014). In order to supply reliable power to the consumer in future, TANGEDCO should implement a good electricity generation expansion plan using LEAP.

LEAP requires the following data for Tamil Nadu to process the scenarios for the base year 2016.

1) Population - 77 Million people (Population of Tamil Nadu, 2016) and Base year demand – 14,800 MW or 122.64 TW h

Table 1
Base values for LEAP including various electricity generation technologies.

Plant Type	Capacity (MW)	Efficiency (%)	Maximum availability (%)	Capacity credit (%)	Capital cost ($\times 10^3$ \$/MW)	Fixed OM Cost (\$/MW)	Variable OM Cost (\$/MW)	Life Time (years)
Natural Gas	1023	35	55	85	600	30	3.6	40
Coal	10180	30	60	85	1400	40	4.47	40
Hydro	2183	90	40	95	2000	14	0	50
Biomass	147.2	60	60	52	2500	90	17.49	40
Nuclear	1000	40	80	90	2600	90	2.14	50
Diesel	429.3	35	55	90	1500	50	8.2	30
Wind	7948.8	40	27	35	1200	39	0	40
Solar	307.98	20	20	30	5500	27	0	30

(14,800 MW × 8760 h = 122.64 TW h) (Load Generation Balance Report 2016-17, 2017Load Generation Balance Report 2016-17, 2017).

2) Gross state domestic product (GSDP) – 140 Billion US \$. GSDP per capita growth rate is assessed as 8.5% (Indian States, 2016).
3) Electricity demand – Residential: 47.2 Million MWh, Industries: 69.8 Million MWh, Transport: 0.8 Million MWh (Electricity, 2017).
4) As per the report “Economic Survey 2016-17″, Ministry of Finance, Government of India, the annual average growth rate of Tamil Nadu is fixed as 6% (Economic Survey 2016-17, 2017Economic Survey 2016-17, 2017).
5) Transformation Data - The LEAP model for Tamil Nadu has been developed by setting the base values shown in Table 1. The transmission losses are taken as 18% for developing the model (Sharma, 2016). The planning reserve margin is assumed as 40% (Kannan et al., 2005; Rajesh, Karthikeya, Kannan, & Thangaraj, 2016). This data for various electricity generation technologies is taken from (Annual Energy Outlook, 2015; Efficiency in Electricity Generation, 2003; Energy Technology Perspectives, 2012; Updated Capital Cost Estimates for Utility Scale Electricity Generating Plants, 2013). These data are entered into the Transformation module called ‘Electricity Generation’ in the LEAP model that includes various electricity generation plants namely wind, solar, biogas, nuclear, hydro, diesel, natural gas and coal. The capital cost, fuel cost, fixed and variable operation and maintenance cost, efficiency, maximum availability, capacity credit, lifetime, system load curve and a planning reserve margin are given as input data. The discount rate is set to 5% for cost data.
6) Environmental Data - For GHG mitigation assessment, the emission factors published by the IPCC (The IPCC’s online EFDB database is a key source of data on emission factors, 2016) are applied to the LEAP model.

Table 1 provides the data such as capacity, efficiency, maximum availability, capacity credit, different costs and life time of the power plants proposed to be installed. The efficiency, capacity credit and the availability of conventional power plants are higher than RES, because RES are intermittent in nature. Hence a very huge amount of RES penetration is required to satisfy the demand. So, the value of overall installation capacity of RES will be higher than the conventional plants. In the context of cost estimation, even though the capital investment cost of RES is high, the overall cost for long-term operation will become low because of its very low operation and maintenance (OM) cost. Most importantly, the emission is almost zero in RES based power generation.

Fig. 1 shows the process of electricity generation expansion planning for Tamil Nadu using LEAP and EnergyPLAN.

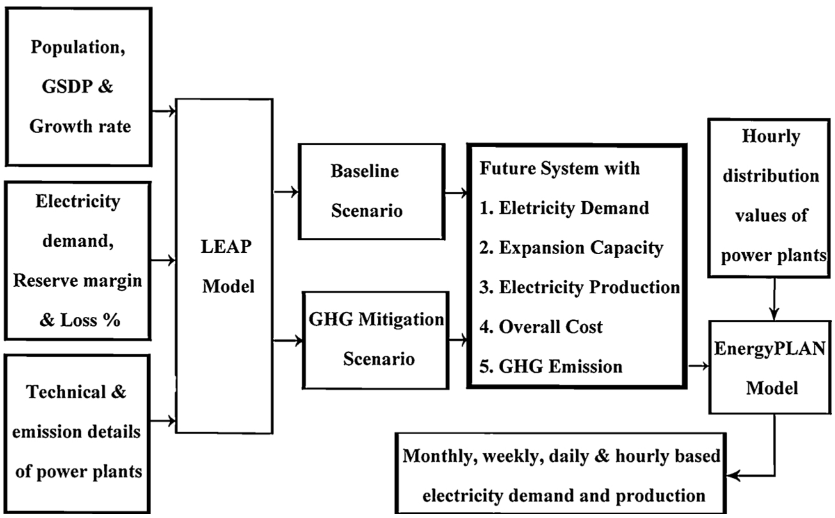

Fig. 1. Process of GEP using LEAP and EnergyPLAN.

LEAP flexibly offers a comprehensive, integrated model that consider demand-side and supply-side energy sector mitigation options. Moreover, it provides a platform for the calculation of costs and emissions impacts. The developed LEAP model for Tamil Nadu has two different cases such as baseline scenario and GHG mitigation scenario. To perform baseline scenario, data for the base year are given to LEAP. LEAP selects any one among interpolation, extrapolation function and the growth rate method to compute the future energy requirements and emissions for the other years. In GHG mitigation scenario, LEAP calculates the optimal expansion of power plants for the electricity system for less GHG emission and subject to the constraints such as least cost and minimum or maximum capacities, for certain plant types.

There are three main steps in developing LEAP model, each with several sub-steps, as follows:

3.1. Design and set up for analysis

Mitigation analysis requires data on emissions, socio-economic variables, and specific mitigation options of energy systems. Single or multiple approaches are required to establish mitigation options. In general, this process includes the following steps:

1) Selection of base year as 2016 and time horizon till 2030.
2) Accession of required data and related information.
3) Choosing the modeling approach depending on the available energy data, selected model, and the relation between energy sectors and end users. The data structure used in the modeling is represented in terms of present as well as projected GHG emissions and the mitigation options. The model relationships or formulations are the algorithms or equations that relate activities (e.g. value added, population growth, etc.) on the demand side energy utility. They command the operating characteristics of energy conversion and supply facilities. These relationships will depend on local conditions and apparent behavioral and functional relationships.
4) Normalization of the disaggregated energy data to get the accurate national energy supply totals for the base year.
5) Specification of the gases and emission factors that calibrates base year emissions with existing GHG inventories, as available.

3.2. Development of baseline scenario

If there are no steps taken to limit GHG emissions the baseline scenario plans energy use and emissions over the selected time horizon, considering development of the national economy and energy system. The baseline scenario is defined with the assumptions for economic and demographic parameters, changes in energy use patterns, fuel costs, and technological data. These assumptions are based on available macroeconomic modeling projections, government energy sector investment plans, and analyst judgment.

3.3. Development of GHG mitigation scenario

This process includes several sub-steps:

1) Setting the objective of the scenario to meet GHG emission reduction and to assess particular policies or technologies.
2) Selection of target (CO_2 or GHG). This study considers six types of GHG as mentioned in Table 6.
3) Fixation of discount rate as 5% and defining the costs and benefits that are to be included.
4) Runs the developed energy sector model of Tamil Nadu to calculate costs and overall GHG emissions through the time horizon considered.
5) Conducts sensitivity analysis with the baseline scenario.

LEAP estimates the electricity demand till the year 2030 with the fixed annual average growth rate of 6% and it is given in Table 2.

4. Results and discussions

The results of LEAP for baseline scenario and GHG mitigation scenario until the year 2030 are discussed.

4.1. Case 1: baseline scenario

In this case, a basic scenario has been simulated based on growth rate method. Based on standard simulation calculations, LEAP decides the time of installation and types of power plants to be installed. The estimated values of installation capacity, energy

Table 2
Electricity demand for Tamil Nadu till 2030 estimated by LEAP.

Electricity Demand (TWh)	Years													
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
	124.32	130.86	137.40	143.94	151.72	159.49	167.27	175.04	182.82	190.59	198.37	206.14	213.92	221.69

Table 3
Installation capacities of various power plants planned by baseline scenario of LEAP.

Capacity to be installed (GW)	Years													
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Hydro	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
Coal	29.58	31.08	32.58	34.08	36.08	38.08	40.08	41.58	43.58	45.58	47.58	49.08	51.08	53.08
Oil	11.81	13.01	13.91	14.81	16.01	16.91	18.11	19.31	20.21	21.41	22.61	23.81	24.71	25.91
Nuclear	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Natural Gas	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
Wind	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86	7.86
Solar	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17	0.17
Biomass	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39	0.39
Total	54.00	56.70	59.10	61.50	64.70	67.60	70.80	73.50	76.40	79.60	82.80	85.50	88.40	91.60

generation, overall cost and GHG emission, until the year 2030 for baseline scenario are given in Tables 3–6 respectively.

The results for baseline scenario show that all the power plants except coal plant have the same expansion capacity throughout the planning horizon. The coal plants have good process efficiency, capacity credit value and availability than other plants. By considering these advantages of coal plants, the baseline scenario expands coal plants only throughout the planning horizon to satisfy the increasing demand as represented in Table 3. But, this baseline scenario didn't consider the GHG emission control. The values of GHG emission in Million Tons of CO_2 Equivalent are shown in Table 6. The coal power plant emits more amount of pollutants and the total GHG emission is very high. Even though more than ten different GHG are available in atmosphere (Greenhouse gas, 2017), the most important and highly emitted gases from power plants are considered in this paper as provided in Table 6. Among them, CO_2 is the most prominent GHG component, because it contributes more than 98% in GHG emission while generating electricity. The electrical energy that can be produced through the installation capacity with respect to the efficiency of each power plant is provided in Table 4. The fuel production cost for coal power plant is high, henceforth the overall cost for producing electricity is very high and is presented in Table 5.

4.2. Case 2: GHG mitigation scenario

The GHG mitigation scenario allows LEAP to decide the combination of power plants that meets the demand with least GHG emission. The combinations of power plants is optimized by LEAP ensuing the merit order scheme. The merit order values are parameterized as 1 for wind, solar, natural gas and hydro and 2 for coal, oil, nuclear and biomass plants. Consequently the LEAP gives more preference to the plants which have merit order as 1, for generating electricity. The installation capacity, energy generation, overall cost and GHG emission until the year 2030 for GHG mitigation scenario are given in Tables 7–10 respectively.

The ultimatum of this case is to give more preference to RES for generating electrical energy in order to limit the GHG emission. Tables 7 and 8 provide the fuel combinations of power plants and electrical energy output till the year 2030. The results shows the RES would be installed more than other plants. The capital cost would be increased in this case and is given in Table 9. The total GHG emission will be reduced very much due to the installation of more number of RES based power plants and is given in Table 10. Figs. 2 and 3 illustrate the total GHG emission while generating electricity for baseline scenario and GHG mitigation scenario till the year 2030 planned by LEAP.

4.3. Monthly and hourly basis GEP using EnergyPLAN

EnergyPLAN relies on analytical programming, with the same input that will always come up with same results. This model performs the calculation on the basis of RES data of stochastic and intermittent nature. It is an hour-simulation model against the

Table 4
Electrical energy can be produced by the installation capacity planned by baseline scenario of LEAP.

Electrical energy to be produced (TWh)	Years													
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Hydro	17.20	17.20	17.20	17.20	17.20	17.20	17.20	17.20	17.20	17.20	17.20	17.20	17.20	17.20
Coal	77.71	82.44	87.68	92.90	99.06	105.74	111.89	117.60	124.22	130.38	136.54	142.03	148.61	154.76
Oil	28.45	31.64	34.32	37.02	40.30	43.05	46.36	50.07	52.82	56.15	59.49	63.17	65.91	69.26
Nuclear	3.45	3.49	3.54	3.58	3.61	3.65	3.67	3.72	3.75	3.76	3.77	3.80	3.83	3.83
Natural Gas	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94	4.94
Wind	18.59	18.59	18.59	18.59	18.59	18.59	18.59	18.59	18.59	18.59	18.59	18.59	18.59	18.59
Solar	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24	0.24
Biomass	1.02	1.03	1.05	1.06	1.07	1.08	1.09	1.10	1.11	1.11	1.12	1.13	1.13	1.13
Total	151.61	159.59	167.56	175.54	185.02	194.51	203.99	213.47	222.88	232.39	241.90	251.11	260.46	269.97

Table 5
Overall cost for electricity production estimated by baseline scenario of LEAP.

Overall cost (Billion U.S. Dollars)	Years													
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Capital	0.18	0.39	0.57	0.75	1.00	1.23	1.47	1.67	1.90	2.15	2.39	2.59	2.82	3.06
Fixed O&M	1.97	2.06	2.14	2.23	2.34	2.44	2.55	2.64	2.75	2.86	2.97	3.06	3.17	3.28
Variable O&M	0.47	0.50	0.53	0.56	0.60	0.64	0.68	0.71	0.75	0.79	0.83	0.86	0.90	0.94
Total	2.62	2.94	3.24	3.54	3.94	4.30	4.70	5.03	5.40	5.79	6.19	6.52	6.88	7.28

Table 6
Total GHG emission while generating electricity estimated by baseline scenario of LEAP.

GHG Components (Million Tons)	Years													
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Carbon Dioxide	72.03	77.29	82.59	87.90	94.22	100.59	106.92	113.17	119.50	125.85	132.21	138.29	144.58	150.93
Carbon Monoxide	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.02	0.03	0.03	0.03	0.03	0.03	0.03
Non Methane Volatile Organic Compounds	0.00	0.00	0.00	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Nitrogen Oxides	0.23	0.24	0.26	0.27	0.29	0.31	0.33	0.35	0.37	0.39	0.41	0.43	0.45	0.47
Nitrous Oxide	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfur Dioxide	0.80	0.86	0.92	0.98	1.05	1.12	1.20	1.27	1.34	1.41	1.48	1.55	1.62	1.69
Total	73.07	78.41	83.79	89.18	95.59	102.06	108.48	114.83	121.25	127.69	134.14	140.31	146.70	153.14

Table 7
Installation capacities of various power plants planned by GHG mitigation scenario of LEAP.

Capacity to be installed (GW)	Years													
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Hydro	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18	2.18
Coal	10.08	10.08	10.08	10.08	10.08	10.08	10.08	10.08	10.08	10.08	10.08	10.08	10.08	10.08
Oil	28.01	28.01	28.01	28.01	28.01	28.01	28.01	28.01	28.01	28.01	28.01	28.01	28.01	28.01
Nuclear	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Natural Gas	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03	1.03
Wind	10.56	13.46	16.26	19.16	22.66	26.06	29.46	32.96	36.36	39.76	43.26	46.66	50.06	53.56
Solar	2.77	5.67	8.57	11.47	14.87	18.27	21.77	25.17	28.57	32.07	35.47	38.87	42.37	45.77
Biomass	0.91	1.49	2.07	2.63	3.33	4.01	4.69	5.39	6.07	6.75	7.45	8.13	8.81	9.51
Total	56.52	62.90	69.18	75.54	83.14	90.62	98.20	105.80	113.28	120.86	128.46	135.94	143.52	151.12

Table 8
Electrical energy to be produced by the installation capacity planned by GHG mitigation scenario of LEAP.

Electrical energy to be produced (TWh)	Years													
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Hydro	15.20	14.87	14.61	14.31	14.01	13.76	13.56	13.38	13.23	13.10	12.94	12.80	12.68	12.56
Coal	46.79	45.78	44.98	44.05	43.11	42.37	41.73	41.17	40.72	40.31	39.84	39.41	39.02	38.66
Oil	48.76	46.92	45.21	44.22	42.95	41.81	40.61	39.35	38.21	37.01	36.28	35.80	35.29	34.66
Nuclear	6.11	5.97	5.87	5.75	5.63	5.53	5.45	5.37	5.31	5.26	5.20	5.14	5.09	5.04
Natural Gas	4.37	4.27	4.20	4.11	4.02	3.96	3.90	3.84	3.80	3.76	3.72	3.68	3.64	3.61
Wind	22.07	27.52	32.67	37.70	43.63	49.32	54.91	60.62	66.13	71.59	76.98	82.14	87.26	92.49
Solar	3.43	6.87	10.21	13.38	16.97	20.49	24.05	27.43	30.79	34.22	37.40	40.55	43.77	46.84
Biomass	4.22	6.77	9.24	11.50	14.25	16.86	19.42	22.02	24.53	27.00	29.45	31.80	34.12	36.49
Total	150.95	158.99	166.99	175.01	184.57	194.10	203.63	213.19	222.72	232.25	241.81	251.34	260.87	270.36

model based on annual demands and generation. Consequently, the model can examine the influence of fluctuating RES on the system as well as weekly and seasonal variations in electricity. The results obtained by GHG mitigation scenario in LEAP are given as input to EnergyPlan. The estimated value of electrical energy demand for the year 2030 is 221.69 TW h, which is provided as the input for EnergyPLAN.

In EnergyPLAN model, electricity is considered as the only demand and the available capacity of various power plants in the year 2030 (From Table 7) are given as input in the supply branch of the EnergyPLAN model. The input data are given to the EnergyPLAN

Table 9
Overall cost for electricity production estimated by GHG mitigation scenario of LEAP.

Overall cost (Billion U.S. Dollars)	Years													
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Capital	1.23	2.58	3.93	5.29	6.89	8.49	10.11	11.72	13.31	14.94	16.54	18.13	19.76	21.37
Fixed O&M	1.95	2.20	2.46	2.71	3.02	3.32	3.62	3.93	4.23	4.53	4.84	5.14	5.44	5.75
Variable O&M	0.41	0.41	0.42	0.42	0.43	0.43	0.44	0.45	0.45	0.46	0.47	0.48	0.49	0.50
Total	3.59	5.20	6.81	8.42	10.34	12.24	14.18	16.09	17.99	19.93	21.85	23.75	25.69	27.61

Table 10
Total GHG emission while generating electricity estimated by GHG mitigation scenario of LEAP.

GHG Components (Million Tons)	Years													
	2017	2018	2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029	2030
Carbon Dioxide	62.15	60.34	58.76	57.51	56.09	54.88	53.72	52.58	51.57	50.58	49.81	49.22	48.64	48.01
Carbon Monoxide	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.01
Non Methane Volatile Organic Compounds	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Nitrogen Oxides	0.19	0.18	0.18	0.17	0.17	0.17	0.16	0.16	0.16	0.15	0.15	0.15	0.15	0.15
Nitrous Oxide	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sulfur Dioxide	0.74	0.72	0.70	0.68	0.66	0.65	0.64	0.62	0.61	0.60	0.59	0.58	0.57	0.56
Total	63.09	61.25	59.65	58.38	56.94	55.72	54.54	53.37	52.35	51.34	50.56	49.96	49.38	48.74

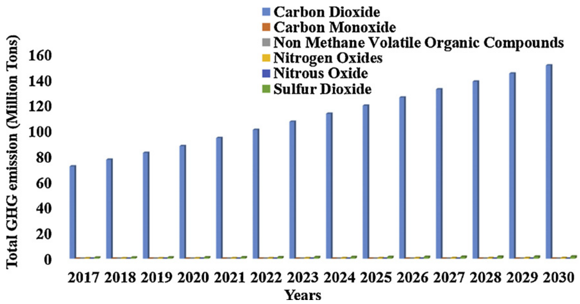

Fig. 2. Estimated total GHG emission planned by baseline scenario of LEAP.

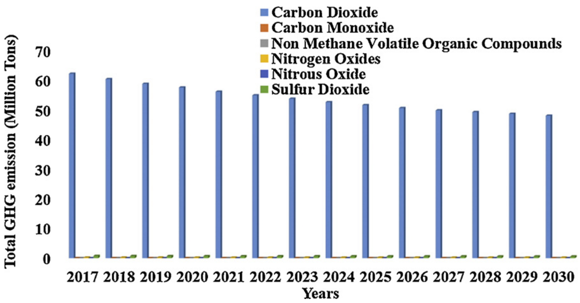

Fig. 3. Estimated total GHG emission planned by GHG mitigation scenario of LEAP.

in two branches where the first branch has the central power plants such as coal, natural gas and diesel are combined together. The second branch has the RES such as solar, wind and biomass. The hourly distribution values (8784 h) for Tamil Nadu, of different power plants are considered depending on their electricity generating capability and seasonal conditions and given as input for EnergyPLAN.

EnergyPLAN model calculates the monthly and hour by hour electricity demand as well as the contribution of different power plants including RES to satisfy the demand. The output from the EnergyPLAN shows the electricity demand in MW, contribution of different power plants to meet the demand and total electricity production that are given in Table 11.

Fig. 4 illustrates the monthly electricity production that meets the demand using different power plants.

The results from the EnergyPLAN show that nuclear and hydro plants could contribute consistently to satisfy the electricity demand. Wind plants generate more electricity during the months January, February, October, November and December. The hourly

Table 11
Monthly electricity production using different power plants during the year 2030.

Months	Electricity Demand (MW)	Production of different power plants (MW)						Total Production (MW)
		Solar	Wind	Biomass	Nuclear	Hydro	Coal + Natural Gas + Diesel	
January	30156	440	10701	6234	979	2180	9708	30242
February	28767	2398	10556	5963	961	2180	6763	28821
March	27429	3334	10191	6225	829	2180	5068	27827
April	23340	8347	8714	3079	796	2180	313	23429
May	22602	9325	7071	3066	893	2180	275	22810
June	21771	8777	6576	3090	893	2180	324	21840
July	20232	6945	5791	4840	947	2180	270	20973
August	23181	5627	6445	5798	957	2180	2226	23233
September	23973	5036	5447	4955	807	2180	5574	23999
October	25126	3169	6680	5851	861	2180	6567	25308
November	27716	975	7882	6003	947	2180	9787	27774
December	29728	549	8887	5972	990	2180	11231	29809
Average Values	25335.08	4576.83	7911.75	5089.66	905	2180	4842.16	25505.41

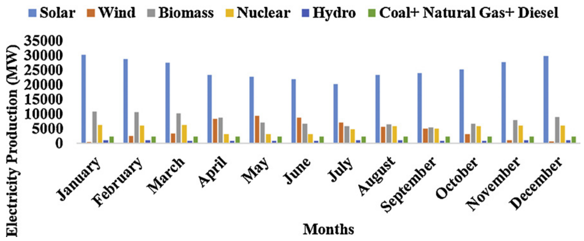

Fig. 4. Expected monthly electricity production during the year 2030 in Tamil Nadu.

basis electricity production of a randomly chosen day (September 26) of the year 2030 is given in Table 12 and also demonstrated in Fig. 5.

Table 12 shows that a maximum demand of 40,391 MW occurs during the 11th hour on September 26, 2030. The demand is high

Table 12
Hourly electricity production to satisfy the demand using different power plants will be on September 26, 2030 for Tamil Nadu.

Hours	Electricity Demand (MW)	Production of different power plants (MW)						Total Production (MW)
		Solar	Wind	Biomass	Nuclear	Hydro	Coal + Natural Gas + Diesel	
1	22385	0	13054	3201	807	2180	4179	23421
2	21870	0	13078	3404	807	2180	4225	23694
3	21738	0	13096	3590	807	2180	3171	22844
4	22131	0	13102	3684	807	2180	3002	22775
5	23937	0	13090	4290	807	2180	4571	24938
6	28525	0	14125	6377	807	2180	5193	28682
7	35131	0	15060	7963	807	2180	9547	35557
8	38723	2150	15054	6825	807	2180	12133	39149
9	39478	3100	12066	7060	807	2180	14646	39859
10	40168	4118	12084	7290	807	2180	14917	41396
11	40391	4737	12090	7459	807	2180	13634	40907
12	39382	4345	11125	9972	807	2180	11875	40304
13	39557	3469	14616	1546	807	2180	17384	40002
14	39017	3015	17125	880	807	2180	15279	39286
15	37165	2065	15233	7489	807	2180	10236	38010
16	35551	581	9706	14290	807	2180	8132	35696
17	36662	0	14125	12769	807	2180	7863	37744
18	36767	0	14706	11223	807	2180	8363	37279
19	36320	0	14706	9304	807	2180	9547	36544
20	35689	0	19233	5409	807	2180	9674	37303
21	33954	0	19233	4763	807	2180	8540	35523
22	31312	0	17251	4290	807	2180	6917	31445
23	27894	0	16137	4290	807	2180	5725	29139
24	25522	0	14706	4002	807	2180	4703	26398
Average value	32886.20	1149.16	14325.04	6307.08	807	2180	8894	33662.29

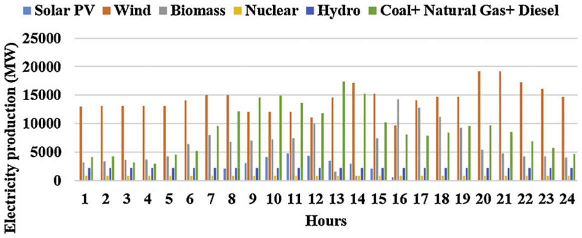

Fig. 5. Expected hourly electricity production during September 26 of the year 2030.

during 7–13 hours and 17–20 hours. The availability of hydropower is high during the month of September. Hence, it can be used in more amount to satisfy the demand during that month. Nuclear plants would generate consistent power throughout the day. These nuclear and hydro plants with huge installed capacities are operated at constant power in the base-load mode (Lokhov, 2015). And they are operated as load-following power plants. The conventional plants (coal, natural gas and diesel) produce more electricity during the peak demand and the solar and wind power are also utilized during their availability.

4.4. Policy implications

Even though, LEAP software has been used at different scales ranging from cities and states to national, regional and global applications by government and non-governmental organizations, academics, consulting companies, and energy utilities in more than 190 countries worldwide, a successful implementation in the nearest state or country with similar circumstances (Population, economic and climate conditions) alone will provide more confidence to the decision makers to pick up and follow an appropriate policy. Recently, in developing countries including India, in most of the case studies LEAP has been applied for transport and energy sectors in the context of GHG emission reduction (Aggarwal, 2017; Hong, Chung, Kim, & Chun, 2016; LEAP, 2017; Sadri, Ardehali, & Amirnekooei, 2014). China, a neighboring country to India, almost similar in terms of population, growth rate, economic and climatic conditions successfully adopted the LEAP based GHG emission reduction policy for generating power (C. Heaps, 2009; Matsumoto, 2015). These studies concluded that by adopting “Deep Carbon Reduction Scenario” in LEAP, the GHG emission could be reduced by 15% in China by the year 2050. With the similar context, the effects of introducing RES in power sector and the CO_2 emissions are evaluated by developing various scenarios under the least cost approach. The results imply that the ARET (Accelerated Renewable Energy Technology) scenario integrates 23% of RES and reduces 74% of CO_2 emission by the year 2050.

Karnataka, the neighboring state of Tamil Nadu, have well trained power system planners to implement the GHG mitigation policy (CSTEP, 2017). The government of Karnataka forces the power sector to reduce the GHG emission from power plants by penetrating huge RES. Therefore, now, the state of Karnataka is self-satisfied in its electricity demand and would be a surplus state in the future (Shivakumar, 2017). But, Tamil Nadu purchases the solar power at a cost of Rs. 7.01 per kWh (0.1 $ per kWh) (Solar Power, 2016). If the policy suggested in this paper is adopted, the solar price will become Rs. 4 per kWh (0.058 $ per kWh). Tamil Nadu which is the 6th most populated state in India has 100% electrified households and due to growing population and industrialization the demand for energy is indispensable. The Vision Tamil Nadu 2023; Strategic Plan for Infrastructure Development in Tamil Nadu stated that an amount of 389,335 Crore of Rupees (56.6 Billion $) had been sanctioned already for power sector. Among that, an amount of 122,372 Crore of Rupees (17.78 Billion $) had been allocated for RES. Also, the Adani group has commissioned to set up 648 MW of solar plant at Kamuthi, near Ramanathapuram, in Tamil Nadu with an investment of Rs 4550 crore (0.66 Billion $) (Kamuthi Solar Power Project, 2017). It is a part of the state government's ambitious target of generating 3000 MW as per the solar energy policy unveiled by the government in 2012 (Resolution, 2010). The entire 648 MW plant is now ready to be connected with Kamuthi 400 kV sub-station of Tamil Nadu Transmission Corporation Ltd, making it the world's second largest solar unit at a single location. The results show that the penetration of RES with fuel mix more than 70% would give reliable power supply within the money sanctioned by the government.

With the similar context for emission, Tamil Nadu Carbon Footprint study carried out by Confederation of Indian Industry (CII) indicates a total GHG emission as 111.86 Million Tons (Estimation of Tamil Nadu’s Carbon Footprint, 2012). In this, power generation contributes 51.42 Million Tons. If the future power generation is planned without considering GHG emission mitigation, the emission would reach 153.14 Million Tons by the year 2030 as resulted in baseline scenario. It is three times higher than the current emission rate. If the GHG mitigation scenario is adopted for future generation expansion, the emission could be restricted to 48.74 Million Tons. It is 5.3% lower than the current emission rate as well as more than three times lower than baseline scenario.

But, the increasing overall cost in GHG mitigation scenario creates a hesitation to the decision makers to follow that scenario. According to the recent report from the World Economic Forum (WEF), solar and wind power is now either the same price or cheaper than power generation from fossil fuels in more than 30 countries including India (World Economic Forum, 2016). Also, it states that ten years ago, the solar cost was $600 per MWh for electricity production and it costs only $100 per MWh through coal and natural gas. Due to the recent developments in RES, it only costs around $100 per MWh through solar and $50 through wind. In future it is expected that the cost for power production through RES will reduce a lot. So, the suggested GHG mitigation scenario would be successful in terms of economic as well as environmental perspectives. Moreover, other states of the country confront a similar pattern of energy demand which could be resolved by implementing the postulated model for the state of Tamil Nadu.

5. Conclusion

Electricity sector is the primary source of greenhouse gases (GHG) emissions around the globe. In order to reduce the GHG emission and to save public health and environment, it is necessary to choose power sources that emit the least CO_2 and methane emissions during electricity generation. This study proposes, the Long-Range Energy Alternative Planning (LEAP) model including baseline scenario and GHG mitigation scenario along with EnergyPLAN model to plan the electricity generation expansion for Tamil Nadu till the year 2030.

In baseline scenario, 91.60 GW total capacity of power plants will produce 269.97 TW h of energy to meet a demand of 221.69 TW h in 2030, with an overall cost of 7.28 Billion U.S. Dollars. They emit 153.14 Million Tons of GHG components.

In GHG mitigation scenario, 151.12 GW total capacity of power plants will produce 270.36 TW h of energy to meet a demand of 221.69 TW h in 2030, with an overall cost of 27.61 Billion U.S. Dollars. They emit 48.74 Million Tons of GHG components. The process efficiency of RES is lower than conventional plants. So huge amount of installed capacity (151.12 GW) is required to meet the energy demand (221.69 TW h). Moreover, the investment cost of RES is higher than that of conventional plants. So the overall cost would become high (27.61 Billion U.S. Dollars). RES which have very low CO_2 emission would emit 48.74 Million Tons of GHG components. Power plants are responsible for 60% of CO_2 emission in India. So the reduction of this gas from power plants makes a huge impact in confining overall CO_2 emission. The results of baseline scenario shows that only 13% of the overall installation capacity is RES (including hydro plants) for the year 2030. But the GHG mitigation scenario suggests to install 74% of overall installation capacity as RES. The overall GHG emission is reduced in GHG mitigation scenario than baseline scenario by 104.4 Million Tons of CO_2 equivalent, but the overall cost is increased by 20.33 Billion U.S. Dollars due to the high capital cost of RES. The GHG mitigation scenario of LEAP model gives optimal results in terms of low GHG emission. The LEAP model plans the electricity generation expansion only on an yearly basis. With the results of GHG mitigation scenario and the data of hourly distribution values of different power plants in Tamil Nadu, the monthly and hourly basis electricity generation planning have been performed successfully using EnergyPLAN model. The results are verified after doing slight modifications in the input parameters to confirm the robustness. The results are nearly the same while varying the inputs slightly. So, a combination of these two models alone offers the best plan on hourly basis for Tamil Nadu's electricity generation expansion and improves the reliability of power supply. The implementation of RES in the power sector will give Tamil Nadu more energy independence in the future and would reduce the GHG emissions.

Based on the overall outcomes, the study hypothesize that the developed country could implement 100% RES in their fuel mix with their huge financial support. The developing countries and under developing countries could implement 70% and 30% of RES in their fuel mix due to moderate and poor financial condition respectively. The approach suggested in this paper can also be applied to any developing countries as well as the countries having similar input data. Also, the proposed GEP studies using LEAP along with EnergyPLAN would be an apotheosis for power system planners globally to manage and surmount the present situation of unsafe environmental hazards that are caused due to GHG emitting power plants.

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